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MEMORANDUM REPORT No. 1019

JULY 1956

Air Blast Measurements Around Moving Explosive Charges, Part III (U)

B. F. ARMENDT

J. SPERRAZZA

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DEPARTMENT OF THE ARMY PROJECT No. 5B03-04-002
ORDNANCE RESEARCH AND DEVELOPMENT PROJECT No. TB3-0112

BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

B A L L I S T I C R E S E A R C H L A B O R A T O R I E S

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A B E R D E E N P R O V I N G G R O U N D, M A R Y L A N D

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PREFACE

This paper was originally presented at the Seventh AXP Tripartite Conference, U. S. Naval Ordnance Laboratory, White Oak, Maryland in April, 1956. Subsequently, D. J. Hinz of the Ballistic Research Laboratories has obtained additional data which appear to corroborate statements made in the paper. A brief discussion of his results is included as an Addendum.

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B A L L I S T I C R E S E A R C H L A B O R A T O R I E S

MEMORANDUM REPORT NO. 1019

BFArmendt/JSperrazza/plg
Aberdeen Proving Ground, Md.
July 1956

AIR BLAST MEASUREMENTS AROUND MOVING EXPLOSIVE CHARGES, PART III (U)

ABSTRACT

Air blast measurements have been made around 3/8 pound bare spherical charges detonated while moving at supersonic velocity. Experimental peak pressure data are presented and are compared to a theory based on the law of conservation of momentum. Agreement between the theory and experiment appears to be satisfactory. The conclusion, based on this theory, is that the velocity effect will probably be of more significance for relatively small charge weights, and/or at high altitudes.

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INTRODUCTION

Since most warheads containing high explosive are in motion at the instant of detonation, it is of interest to study the effect of this motion on the air blast produced by the weapon. This "velocity effect" was first noticed during aircraft vulnerability firings in the United States and Great Britain, and also during Swiss firing trials (1) of 20mm Oerlikon ammunition against box structures. It appeared that the detonating shells caused an increased amount of damage in the direction of motion, and a decreased amount in the opposite direction. Various explanations of the velocity effect have been advanced (2,3,4) but evaluation of these theories required quantitative data. Therefore, in 1952 experiments were begun at the Ballistic Research Laboratories for the purpose of providing these data. It was felt that the data could be obtained directly by

1. projecting an explosive at a desired terminal velocity,
2. detonating the explosive at a desired position in space, and
3. measuring the blast around the detonation.

Early work was performed by Patterson and Wenig (5), who, after great difficulty, succeeded in projecting a bare sphere of explosive at supersonic velocity and detonating it in flight, thus forming the basic experimental procedure which has since been used in all moving charge experiments at the Ballistic Research Laboratories. Unfortunately, the air blast data obtained at that time was only qualitative, because of the state of development of the instrumentation. The experiments were continued in 1954 by Armendt (6) with only minor modifications in procedure, and resulted in the collection of somewhat better data, but still insufficient to establish any rigorous theory. Further experiments have been conducted and have led to the establishment of a theory by which the behavior of the shock wave produced by the detonation of a moving charge may be explained in part.

EXPERIMENTAL PROCEDURE

Projection of the Charge

The first step in the construction of the moving charge experiments was to choose the type and size of charge and to find some means of projecting it at high velocity. Since even a light metal case on the charge produces fragments of a size and velocity sufficient to interfere with air blast measurements, it was decided to use a bare charge. Because of the symmetry of shock waves produced by spherical charges, a spherical shape was chosen. A number of devices for projecting the charge were suggested, but all were abandoned in favor of a conventional cannon. The caliber, and therefore the charge weight of 3/8 pound, was dictated by the large surplus of 57mm guns. The rifling was bored out, resulting in a smoothbore gun of bore diameter 2.293 inches. Charges were made to fit this bore with a small clearance.

Having settled on the 57mm smoothbore gun and the 3/8 pound bare spherical charge, the problem remained to project the charge from the gun. After a great deal of experimentation (5), Patterson succeeded in projecting 3/8 pound, bare spheres of Composition B at a velocity of about 1700 to 1900 feet per second. For this, he used a propellent charge of 8 ounces of type 5316 powder confined in an M23-A2 57mm brass cartridge case, and a sabot consisting of 3 ounces of absorbent cotton in three separate wads. The main problem was charge breakup, which occurred on about 40% of the shots. More recent work by Armendt (7) resulted in a lower percentage of charge breakup, due to the substitution of fiberglas-reinforced Pentolite for the Composition B used by Patterson. The reinforced Pentolite has been utilized in all recent experimental work.

Detonation of the Charge

After the charges had been successfully projected from the gun, attention was turned to the problem of detonating the charges while in flight and at a desired position. A number of schemes were tried and the one finally settled upon is as follows. The charge is cast in a spherical form with a cylindrical well extending into the charge about 2/3 of the

diameter. (See Figure 1.) In the bottom of the well is placed a tiny bit of Composition C-3 and an M-18 tetryl booster to insure high order detonation. Next comes an M-36 electric detonator. Across the leads of the detonator is placed a small coil made of number 28 copper wire wound on a short length of iron rod. All spaces are carefully packed with Composition C-3 to prevent the setback forces, experienced upon firing, from dislodging any part. The charges fuzed in this manner are fired from the gun through a screen wound with number 40 copper wire. The screen is placed just in front of a stationary coil consisting of three turns of number 4 copper wire approximately 7-1/2 inches in diameter. As the charge passes through the screen and into the stationary coil, the wire screen is broken, triggering an electronic circuit which causes a large condenser to be discharged through the stationary coil. The resulting "pulsed" magnetic field induces a current in the small coil inside the charge, which flows through the electric detonator and detonates the charge. If the orientation of the small coil is unfavorable, insufficient current may be induced and the charge may not fire.

Locating the Point of Detonation

Since the accuracy obtained with the smoothbore gun is not particularly good, and since the magnetic induction system of detonating the charge is not perfect, the point at which detonation occurs will rarely be exactly at the point desired. If the data are to be meaningful, it is necessary that the point of detonation be located fairly accurately. Therefore, two cameras equipped with 1-microsecond electronic shutters were placed 90 degrees apart and 10 feet from the desired point of detonation. When the charge detonates, a photocell device triggers the cameras, taking a picture of the luminous shock wave. By triangulation, the position of the charge at the instant of detonation can be located to within about 1/4 inch. A typical photograph of the detonating charge is shown in Figure 2.

Measurement of Charge Velocity

The velocity with which the charge is projected is measured as follows. After the charge leaves the muzzle of the gun and before it passes through the stationary coil where it is detonated, it passes through two wire screens wound with number 40 copper wire placed about 8 feet apart. Breakage of these

SECTIONAL VIEW OF FUZED CHARGE LOADED IN 57 mm SMOOTHBORE GUN

(NOT TO SCALE)

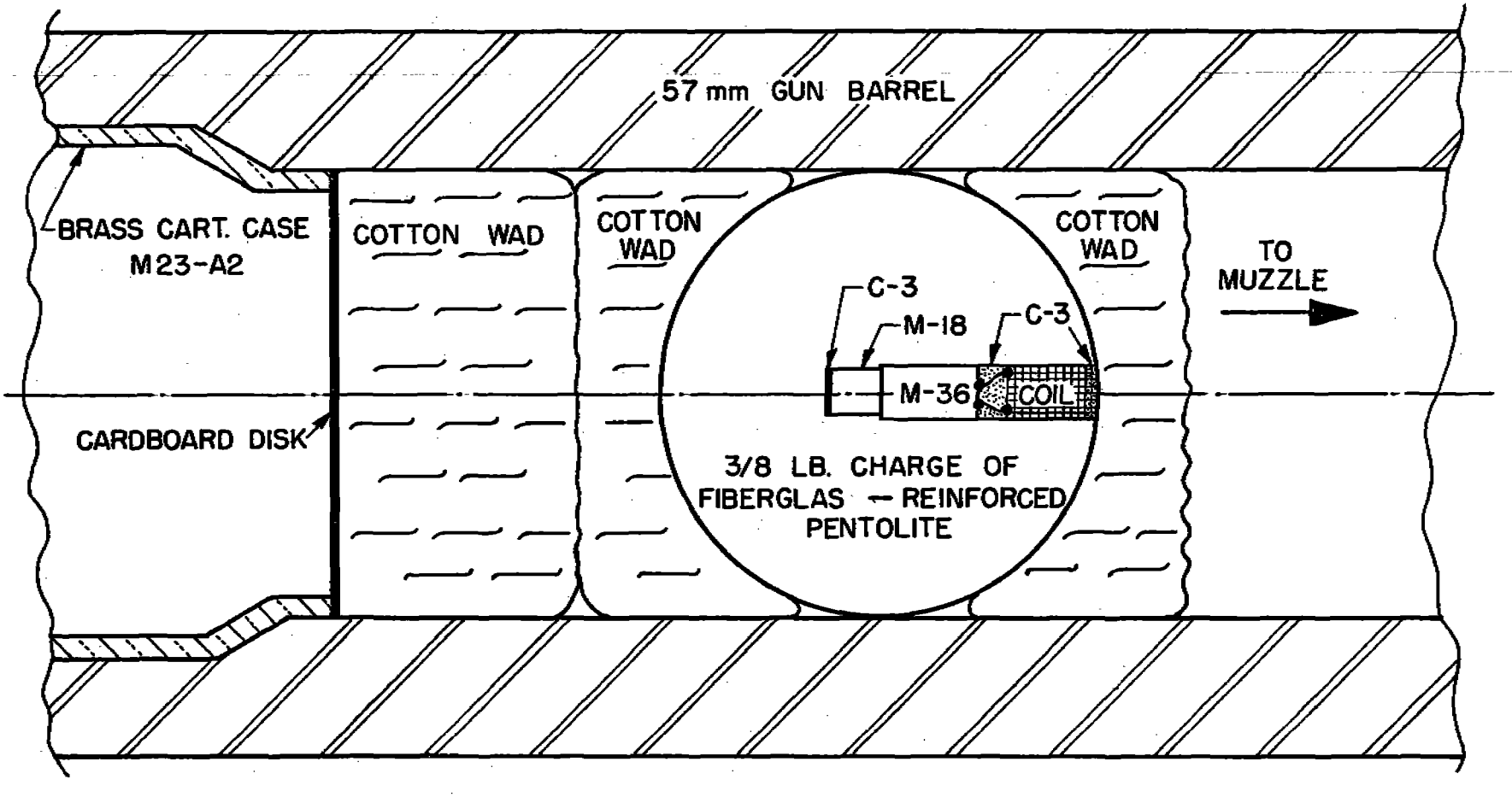

FIGURE 2

screens starts and stops an electronic counter chronograph, thus measuring the time necessary to traverse this interval. From this measurement, the average velocity over the interval can be calculated.

Air Blast Measurements

In the earlier work by Patterson and Wenig, and also by Armendt, the peak pressure and positive impulse of the shock wave produced by the detonation of the moving charge were measured by five pancake-type side-on pressure gages placed at different points around the detonating charge. It became evident, however, that more instrumentation would be required if useful data were to be obtained. Therefore, in recent experiments, a total of twelve side-on pressure gages, each spanned by a pair of face-on "velocity" gages, have been used. (See Figure 3.) The side-on gages were placed at a distance of 2.71 feet from the desired point of detonation, and at angles of 15°, 45°, 75°, 105°, 135°, and 165° from the direction of motion of the charge. The electrical output of each of these side-on gages was amplified and displayed on an oscilloscope. The face of the oscilloscope was photographed by a streak camera in which the 35mm film was moving approximately 1.25 inches per millisecond. Suitable timing marks were also recorded on the film, providing a time calibration.

When the charge detonates, the initial burst of light from the luminous shock wave is seen by a photocell device which triggers the cameras, as was previously mentioned. This same photocell device also starts twelve electronic counter chronographs. When the shock wave from the detonating charge reaches the first velocity gage at one of the twelve measuring positions, the chronograph corresponding to that position is stopped, giving a measure of the time of arrival, and a second counter chronograph is started. The shock wave sweeps past the first velocity gage, over the side-on pressure gage and finally reaches the rear velocity gage which stops the second counter chronograph. This second chronograph has now measured the time necessary for the shock to traverse the interval between the velocity gages, from which the average shock velocity over the interval can be calculated. Knowing the average shock velocity, the peak pressure at the center of the interval can be calculated by the Rankine-Hugoniot relation:

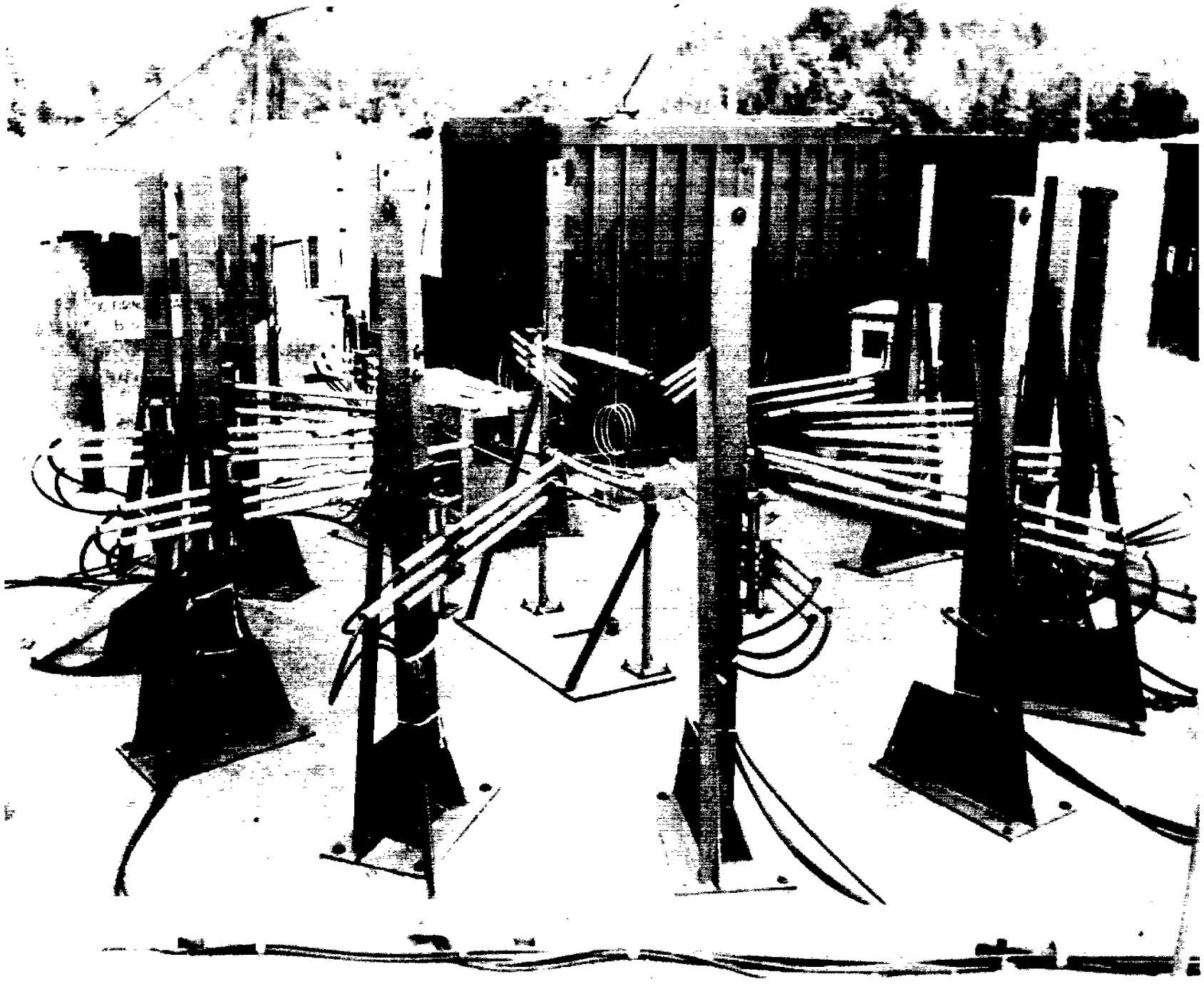

FIGURE 3

$$\frac{P_s}{P_o} = \frac{2\gamma}{\gamma + 1}\left(\frac{V^2}{C^2} - 1\right)$$

where:

P_s = peak excess pressure
P_o = atmospheric pressure
γ = ratio of specific heats for air
V = shock velocity
C = sound velocity

Thus the 24 counter chronographs, 24 velocity gages, and the photocell device make up a system which can measure the shock arrival time, shock velocity, and peak excess pressure at twelve locations around the detonating charge.

DATA

Summaries of the experimental data reported in references 5 and 6 are repeated in Table I and II under appropriate labels. More recent data have been obtained with the experimental setup described above. For the purposes of discussion, these data are separated into two parts, the Time of Arrival Data and the Peak Pressure Data.

Time of Arrival Data

The time of arrival data which were obtained are shown in Table III. It was hoped that these data would tell whether the shock wave from a charge detonated while moving was distorted in any way, or remained spherical. The analysis of the data proceeded as follows: it was noticed that, for a given gage position, although the deviations in distance from the charge resulted in considerable variation in the measured time of arrival, the deviations in angle did not. Therefore, the angular deviations were neglected, and the nominal angles (i.e., 15°, 45°, etc.) were used. This approximation is considered satisfactory, and greatly simplifies the analysis.

Over the small intervals of distance involved, it was assumed that the shock velocity was constant, and therefore, linear least square fits were made to the time of arrival data. The equations for these least square lines are also shown in Table III. In order to determine the shape of the shock wave, these equations were solved for R (distance from the charge)

using values of t_a (time of arrival) equal to 400, 550, and 700 microseconds. The results are plotted in Figure 4.

It appeared that the points fell on a circle whose center was shifted in the direction of motion of the charge. Because of the significance of this result, it was carefully checked by both analytical and graphical methods, but the answer was the same. Therefore, it can be said, that, within the experimental error, the shock wave produced by the detonation of a moving, spherical charge remains spherical, but that the center of the sphere moves in the direction of motion of the charge prior to detonation.

Peak Pressure Data

The peak pressure data obtained from seven rounds are shown in Table IV, under "Experimental Data for Moving Charges." The mean velocity of the seven rounds was 1760 feet/second.

The positive impulse data obtained in the recent firings have not yet been reduced, and therefore, no additional data on positive impulse will be presented at this time.

THEORY

Thornhill and Hetherington (3) predicted that, close to the surface of a moving charge, the shock velocity, and thus inference of the peak pressure, could be approximated by vectorial addition of the shock velocity for the stationary charge and the terminal velocity of the moving charge. Time of arrival measurements, discussed above, indicate that the same rule is applicable to the expanded shock wave, if the velocity of the center is substituted for the terminal velocity of the charge.

Since the radial velocity of shock waves from stationary charges has been measured, it is seen that the position and velocity of the shock front could be described if the velocity of the center of the shock were known as a function of time.

The velocity of the center of the shock wave at any time can be predicted by application of the principle of conservation of linear momentum. Thus the momentum of the explosive prior to detonation is set equal to the momentum of the explosion gases and air contained by the spherical shock, it

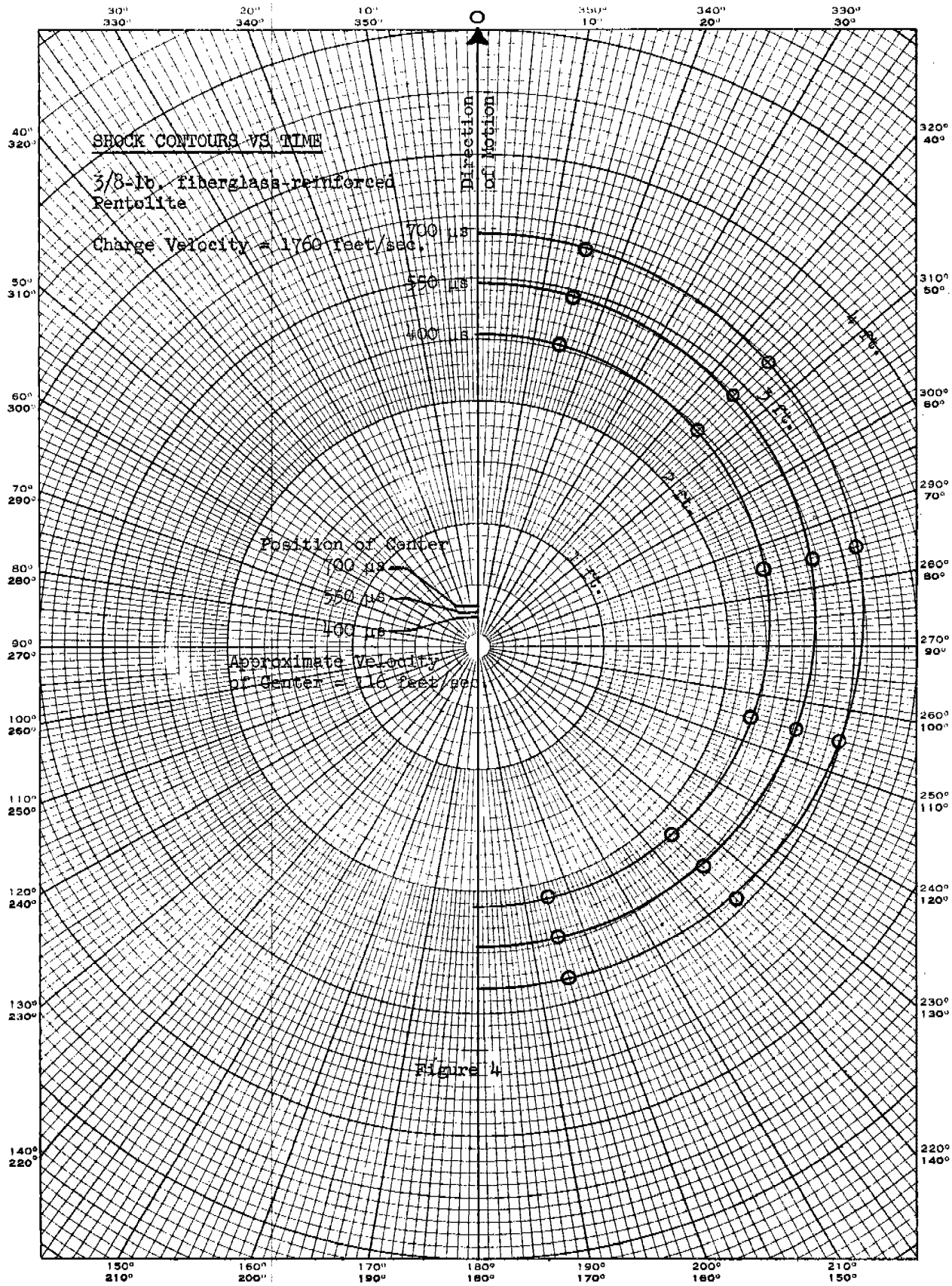
SHOCK CONTOURS VS TIME
3/8-lb. fiberglass-reinforced Pentolite
Charge Velocity = 1760 feet/sec.
Direction of Motion
700 μs
550 μs
400 μs
4 ft.
3 ft.
2 ft.
1 ft.
Position of Center
700 μs
550 μs
400 μs
Approximate Velocity of Center = 116 feet/sec

Figure 4

being assumed that the average velocity of all the contained gases and air is that of the center of the sphere.

Let

M_e = weight of explosive (lbs)
M_a = weight of air contained by the spherical shock (lbs)
V_o = terminal velocity of the explosive (ft/sec)
V_c = velocity of center of shock wave (ft/sec)
d = radius of spherical shock wave (feet)
r = radius of spherical shock wave (charge radii)
a = charge radius (feet)
ρ_a = density of air (lbs/ft^3)
ρ_e = density of explosive (lbs/ft^3)

Neglecting the mass of air displaced by the explosive charge, application of the law of conservation of linear momentum gives:

$$M_e V_o = (M_e + M_a) V_c = (M_e + \frac{4}{3} \pi \rho_a d^3) V_c \qquad (1)$$

or

$$V_c = \frac{M_e V_o}{M_e + \frac{4}{3} \pi \rho_a d^3} \qquad (1\,a)$$

Since

$$M_e = \frac{4}{3} \pi \rho_e a^3 \qquad (2)$$

Equation (1a) reduces to:

$$V_c = \frac{V_o}{1 + \frac{\rho_a}{\rho_e} r^3} \qquad (3)$$

Therefore, at a time when the radius of the shock wave is equal to r, the velocity of the center of the shock wave is given by equation (3). The distance that the center has traveled (in the direction of original charge motion) from the point of detonation at any time t is:

$$r_c = \int_o^t V_c \, dt. \qquad (4)$$

Referred to a stationary frame the shock velocity on the surface of the spherical shock wave produced by the moving charge becomes (see Figure 5):

$$\vec{U}_m = \vec{U}_s + \vec{V}_c$$

Where:

$\vec{U}_m$ = shock velocity at distance r and angle from line of flight ϕ for moving charge.

$\vec{U}_s$ = shock velocity at distance r for stationary charge.

ϕ = angle from line of flight (referred to center of shock wave).

Once the shock velocity is known, the peak pressure can be found.

Ordinarily, the distance r and angle ϕ from the center of the shock wave are not known, measurements being made from the point of detonation. (See Figure 6.) Therefore, the quantities known are R and θ, and, by integration, r_c. The distance and angle from the shock center can be found by:

$$R = r_c \cos \theta + (r^2 - r_c^2 \sin^2 \theta)^{1/2} \qquad (5)$$

$$\sin \phi = \frac{R}{r} \sin \theta$$

Thus far, no simple scheme has been found for scaling the various parameters associated with the velocity effect, such as altitude, charge weight, charge velocity, etc. Therefore, rather lengthy computation is necessary to obtain theoretical values of the peak pressure at various points around a given point of detonation, since each case must be considered individually. These calculations have been made for the conditions obtaining for all of the experimental peak pressure data shown in Table IV. The results are shown in Table IV under "Calculated Data for Moving Charges."

For the purpose of comparing the theory with the experiments, the ratios of the theoretical peak pressures to the experimental peak pressures have been taken, and are also shown in Table IV. The mean value of the ratios is .991 with a standard deviation of the individual of 11.5%. Examination of these ratios has disclosed no systematic error, and it is concluded that the theory adequately approximates the experimental results.

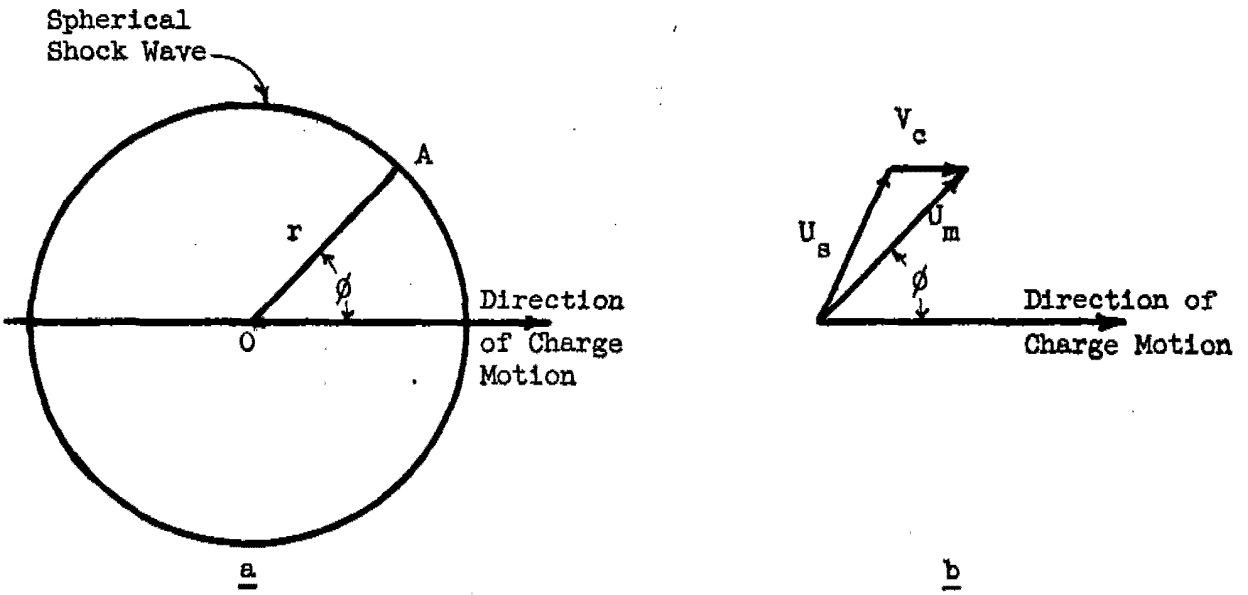

Figure 5

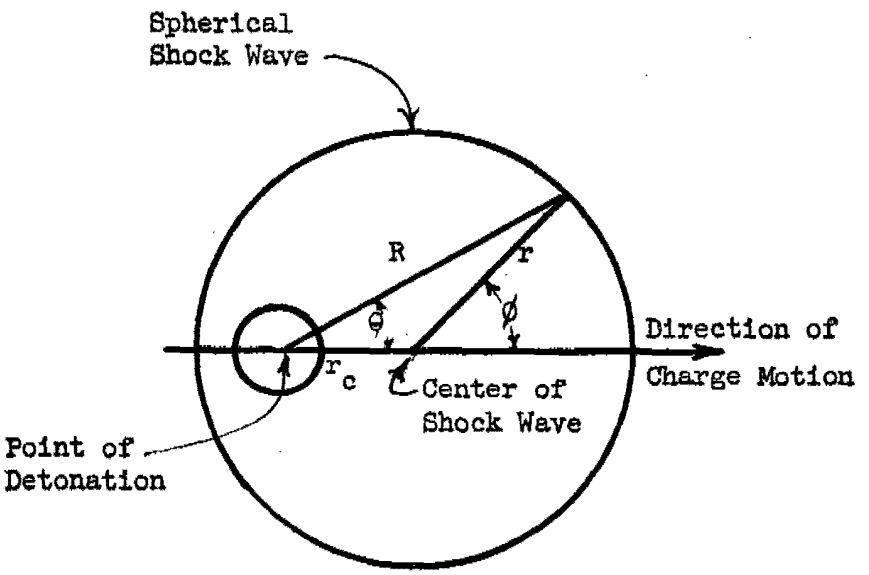

Figure 6

The positive impulse in the shock wave from a moving charge is known to be enhanced in the direction of charge motion (see Tables I and II), but no simple scheme for prediction of the enhancement has been suggested. It is hoped that recently obtained data, now in the process of being reduced, will throw some light on the subject.

COMMENTS

The conclusion is that the theory advanced appears to predict the effect of charge motion on the peak pressure in the shock wave produced when a moving spherical charge is detonated. Furthermore, if this theory is correct, it is seen that the velocity effect would be of greater significance for relatively small charges. With nuclear warheads, for example, the velocity effect would be of little consequence, since at the peak pressure levels where the velocity effect might cause some enhancement of damage, the mass of air contained by the shock wave would far outweigh the original warhead. Only if the weapon were detonated outside the atmosphere and/or if the warhead were moving at very high velocities would the velocity effect be even measurable.

A great deal of work remains to be done before the velocity effect can be completely understood. As previously mentioned, the behavior of the positive impulse requires explanation. Before the peak pressure theory described above can be considered as established, further experiments utilizing higher charge velocities and greater charge weights are necessary. High altitude experiments are especially desirable, since it is expected that the velocity effect will be of much greater significance for low atmospheric pressures. In addition, the effect of a metal casing on the velocity effect must be investigated, since warheads are ordinarily cased.

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TABLE I

SUMMARY OF EXPERIMENTAL DATA FROM BRLM 767

2.36 feet from a 3/8 pound bare, spherical Composition B charge

Charge Velocity	0 ft/sec	1982 ft/sec		
		Angle from Line of Flight		
		15°	45°	105°
Peak Pressure (psi)	73	109	87	55
Positive Impulse (psi-ms)	7.8	14.4	13.0	7.0

TABLE II

SUMMARY OF EXPERIMENTAL DATA FROM BRLM 900

2.71 feet from a 3/8 pound bare, spherical Composition B charge

Charge Velocity	0 ft/sec	1753 ft/sec		
		Angle from Line of Flight		
		15°	45°	105°
Peak Pressure (psi)	67.3	91.0	82.0	52.5
Positive Impulse (psi-ms)	8.1	10.2	9.8	7.9

TABLE III

TIME OF ARRIVAL DATA

Type of charge - 3/8 pound bare, spherical charges of fiberglas-reinforced Pentolite

Mean velocity of charges - 1760 feet/second

Nominal angle from line of flight = 15°

Round No.	Distance from Charge (feet)	Arrival Time (μs)	Distance from Charge (feet)	Arrival Time (μs)
534	2.66	468.8	3.16	628.8
	2.71	480.6	3.21	663.1
578	2.69	443.1	3.19	635.6
	2.69	452.5	3.19	624.4
582	2.56	419.4	3.06	585.7
587	2.45	382.5	2.95	563.8
588	2.73	468.1	-	-
590	2.53	383.1	3.03	556.9
	2.58	428.1	3.08	606.2

Least square fit:

$t_a = 517.1 + 388.2\ (R - 2.846)$

t_a = time of arrival (μs)

R = distance from charge (feet)

Nominal angle from line of flight = 45°

Round No.	Distance from Charge (feet)	Arrival Time (μs)	Distance from Charge (feet)	Arrival Time (μs)
534	2.69	478.1	3.19	686.2
549	2.80	470.0	3.30	701.3
578	2.62	477.5	3.12	676.3
582	2.50	402.5	3.00	584.4
587	2.49	415.0	2.99	598.1
	2.43	388.1	2.93	566.9
590	2.59	438.8	3.09	621.3

Least square fit:

$t_a = 536.0 + 378.7(R - 2.837)$

TABLE III (continued)

Nominal angle from line of flight = 75°

Round No.	Distance from Charge (feet)	Arrival Time (μs)	Distance from Charge (feet)	Arrival Time (μs)
534	2.62	533.1	3.12	748.7
549	2.37	406.9	2.87	573.8
	2.59	530.6	3.09	731.2
578	2.52	465.0	3.02	643.1
	2.54	440.0	3.04	661.3
582	2.45	433.1	2.95	621.9
	2.52	466.3	3.02	668.2
587	2.50	457.5	3.00	655.0
	2.42	421.3	2.92	623.2
588	2.69	516.9	3.19	707.5
	2.37	419.4	2.87	591.3
590	2.40	390.6	2.90	581.9
	2.57	478.8	3.07	676.9

Least square fit:

$$t_a = 555.5 + 398.5 (R - 2.755)$$

Nominal angle from line of flight = 105°

Round No.	Distance from Charge (feet)	Arrival Time (μs)	Distance from Charge (feet)	Arrival Time (μs)
549	2.59	530.0	3.09	747.5
578	2.40	447.5	2.90	653.8
	2.42	475.6	-	-
582	2.47	500.0	-	-
587	2.50	501.3	3.00	714.4
	2.42	471.9	2.92	696.3
588	2.58	497.5	3.08	708.1
	2.24	417.5	2.74	611.3
590	2.35	447.5	-	-
	2.52	510.6	3.02	726.2

Least square fit:

$$t_a = 568.1 + 403.6 (R - 2.662)$$

TABLE III (continued)

Nominal angle from line of flight = 135°

Round No.	Distance from Charge (feet)	Arrival Time (μs)	Distance from Charge (feet)	Arrival Time (μs)
549	2.13	387.5	-	-
578	2.31	466.9	-	-
582	2.37	467.5	2.87	693.8
	2.42	511.2	-	-
587	2.43	505.0	-	-
588	2.43	475.0	-	-
	2.18	415.0	-	-
590	2.46	507.5	-	-

Least square fit:

$$t_a = 492.2 + 399.9 (R - 2.399)$$

Nominal angle from line of flight = 165°

Round No.	Distance from Charge (feet)	Arrival Time (μs)	Distance from Charge (feet)	Arrival Time (μs)
534	2.27	440.0	2.77	653.8
549	2.25	452.5	2.75	643.1
578	2.23	467.5	2.73	673.8
	2.24	476.3	-	-
582	2.37	535.0	2.87	756.9
	2.39	530.0	-	-
587	2.48	560.0	2.98	791.3
	2.45	538.1	-	-
588	2.29	474.4	2.79	676.3
	2.19	439.4	-	-
590	2.35	493.8	2.85	734.4
	2.40	527.5	-	-

Least square fit:

$$t_a = 571.8 + 431.7 (R - 2.506)$$

TABLE IV

EXPERIMENTAL DATA FOR MOVING CHARGES

Type of charge - 3/8 pound bare sphere of fiberglass-reinforced Pentolite
Mean velocity of charge - 1760 feet/second

CALCULATED DATA FOR MOVING CHARGES

COMPARISON

Rd. No.	Atmospheric Temperature (°F)	Atmospheric Pressure (in Hg)	Angle from Line of Flight (degrees)	Distance from Charge (feet)	Shock Velocity (ft/sec)	Peak Pressure (lb/in²)	Distance from Charge (charge radii)	r (charge radii)	r_c (charge radii)	ϕ (degrees)	Center Velocity (V_c) (Mach No.)	Radial Shock Velocity (Mach No.)	Theoretical Peak Pressure (psi)	Ratio of Calc. peak pressure / Exp. peak pressure
534	52	29.80	12.0	2.91	3125	118.3	30.4584	27.8805	2.6438	13.09	.0917	2.2585	75.25	.636
			69.8	2.69	2389	62.0	28.1034	27.3087	2.6203	74.90	.0971	2.2951	74.46	1.200
			161.5	2.52	2389	58.7	26.3764	28.9354	2.6855	163.18	.0825	2.1452	65.66	.948
			71.1	2.87	2319	57.5	30.0502	29.2885	2.6990	76.12	.0797	2.1220	61.02	1.062
			43.2	2.94	2403	62.9	30.7934	28.8957	2.6840	46.85	.0829	2.1526	66.05	1.049
			15.7	2.96	2740	87.0	30.9504	28.3943	2.6647	17.16	.0870	2.1918	71.07	.817
549	74	29.83	10.0	2.95	2614	73.9	30.8457	28.2828	2.6061	10.91	.0878	2.2007	57.16	.773
			38.1	2.80	2847	90.9	29.2757	27.3030	2.5657	41.43	.0970	2.2937	78.39	.862
			67.9	2.62	2996	102.4	27.4335	26.5839	2.5344	72.95	.1046	2.3667	80.87	.790
			159.1	2.50	2623	74.6	26.1461	28.6076	2.6186	160.97	.0851	2.1752	57.71	.774
			98.4	2.84	2299	53.3	29.7153	30.2248	2.6787	103.56	.0728	2.0541	53.70	1.008
			70.7	2.98	2493	65.7	31.1493	30.3657	2.6837	75.42	0.719	2.0443	55.45	.545
			43.7	3.07	2162	45.1	31.8819	30.0089	2.6710	47.26	.0743	2.0692	59.51	1.318
578	70	30.12	13.6	2.94	2597	74.1	30.7306	28.1671	2.6441	14.84	.0895	2.2117	73.64	.994
			41.5	2.87	2515	68.4	30.0816	28.1563	2.6437	45.08	.0898	2.2127	71.92	1.051
			70.2	2.77	2807	89.5	28.9931	28.2078	2.6458	75.27	.0891	2.2075	68.40	.764
			100.1	2.65	2424	62.3	27.7161	28.3022	2.6497	105.40	.0852	2.0990	56.92	.913
			131.4	2.54	2547	70.6	26.5857	28.4107	2.6539	135.42	.0813	2.1905	60.73	.860
			163.8	2.48	2424	62.3	25.9577	28.5207	2.6581	165.33	.0784	2.1820	58.52	.939
			70.4	2.79	2259	51.9	29.2234	28.4420	2.6551	75.43	.0871	2.1881	66.81	1.288
			41.9	2.89	2128	44.1	30.2386	28.3196	2.6503	45.43	.0881	2.1977	70.64	1.603
			14.0	2.94	2909	97.3	30.7934	28.2328	2.6458	15.32	.0933	2.2054	73.06	.751
582	75.5	30.11	13.8	2.79	3041	106.7	29.1606	26.7151	2.5261	15.10	.1022	2.3533	86.22	.808
			43.2	2.75	2749	84.0	28.7628	26.9883	2.5368	46.86	.0996	2.3274	81.46	.970
			73.0	2.70	2648	76.7	28.2499	27.6094	2.5633	78.10	.0932	2.2646	72.50	.945
			103.4	2.65	2403	60.1	27.7685	28.4817	2.5963	108.49	.0854	2.1250	62.90	1.047
			134.2	2.62	2210	48.2	27.4440	29.3390	2.6310	137.89	.0785	2.1150	55.78	1.158
			165.3	2.62	2253	50.8	27.3812	29.9549	2.6532	166.55	.0740	2.0730	51.58	1.016
			73.4	2.77	2477	64.9	28.9826	28.3526	2.5935	78.44	.0864	2.1951	66.97	1.032
			44.3	2.80	2469	64.4	29.2862	27.5110	2.5593	47.97	.0941	2.2739	76.74	1.191
			15.3	2.81	3007	103.9	29.3594	26.9220	2.5348	16.67	.1000	2.3321	84.19	.811
587	78	30.05	15.9	2.72	2817	88.3	28.4593	26.0373	2.5280	17.44	.1123	2.4276	93.12	1.054
			45.7	2.74	2731	82.0	28.6686	26.9376	2.5684	49.62	.1022	2.3307	81.42	.954
			75.3	2.75	2532	68.0	28.8047	28.2534	2.6242	80.46	.0892	2.2035	67.30	.969
			104.8	2.75	2346	56.0	28.8256	29.6241	2.6769	109.85	.0781	2.0961	56.36	1.006
			164.1	2.73	2162	44.9	28.5221	31.1581	2.7316	165.50	.0679	1.9599	46.40	1.033
			105.3	2.67	2228	48.8	27.9359	28.7473	2.6433	110.40	.0852	2.1642	61.07	1.251
			74.8	2.67	2477	64.4	27.9150	27.3517	2.5865	80.07	.0979	2.2891	74.10	1.152
			44.4	2.68	2796	86.8	28.0092	26.2553	2.5382	48.25	.1096	2.4004	87.85	1.012
			14.1	2.70	2758	83.9	28.2185	25.7852	2.5162	15.46	.1154	2.4572	96.06	1.145

[redacted]

TABLE IV (Cont.)

Rd. No.	Atmospheric Temperature (°F)	Atmospheric Pressure (in Hg)	Angle from Line of Flight (degrees)	Distance from Charge (feet)	Shock Velocity (ft/sec)	Peak Pressure (lb/in²)	Distance from Charge (charge radii)	r (charge radii)	r_c (charge radii)	ϕ (degrees)	Center Velocity (V_c) (Mach No.)[c]	Radial Shock Velocity (Mach No.)	Theoretical Peak Pressure (psi)	Ratio of Calc. peak pressure / Exp. peak pressure
			EXPERIMENTAL DATA FOR MOVING CHARGES				CALCULATED DATA FOR MOVING CHARGES							COMPARISON
588	83.5	30.05	71.5	2.94	2623	73.3	30.7725	30.0217	2.7106	76.40	.0757	2.0683	57.52	.784
			99.6	2.83	2374	57.0	29.5897	30.1593	2.7156	104.66	.0747	2.0587	54.27	.953
			160.0	2.54	2477	63.5	26.5857	29.1145	2.6765	161.76	.0823	2.1355	55.48	.874
			100.8	2.49	2580	70.4	26.0938	26.6982	2.5761	106.26	.1053	2.3550	75.66	1.075
			69.1	2.62	2909	94.1	27.4440	26.6357	2.5733	74.29	.1060	2.3614	80.85	.859
590	82	30.04	12.8	2.78	2877	92.1	29.0978	26.5954	2.5723	14.00	.1063	2.3655	87.42	.950
			72.6	2.65	2614	73.0	27.7685	27.1042	2.5950	77.82	.1007	2.3135	76.38	1.047
			166.3	2.60	2078	39.8	27.1928	29.8270	2.7044	167.53	.0770	2.0819	51.92	1.305
			102.7	2.77	2319	53.8	29.0036	29.7123	2.7003	107.75	.0778	2.0900	56.11	1.043
			73.6	2.82	2524	66.9	29.5164	28.8774	2.6681	78.65	.0845	2.2541	63.70	.952
			44.9	2.84	2740	81.9	29.6944	27.8938	2.6285	46.70	.0931	2.2375	73.50	.898
			16.2	2.83	2807	86.8	29.5658	27.0872	2.5943	17.73	.1009	2.3153	82.61	.951
													Mean	.991
													Standard deviation	.114 = 11.5%

r = radius of spherical shock wave.
r_c = distance that center of shock wave has traveled from point of detonation.
ϕ = angle from line of flight with reference to the center of the shock wave instead of the point of detonation.

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1. Oerlikon Machine Tool Works, Zurich-Oerlikon, Switzerland Brochure No. 950, "Target-Velocity and Blasting Effect of 'Oerlikon' 20mm Ammunition."

2. NOL Memorandum No. 10983, "Charge Velocity and Blast Effect - Comments on Oerlikon Report," H. G. Snay, 1 July 1950.

3. ARE Memo 6153, "Some Notes on Explosions of Moving Charges," C. K. Thornhill and R. Hetherington, April 1953.

4. Rand Report RM-848, "Note on Directional Effect of Pressure Field of Moving Blast," J. D. Cole, 9 June 1952.

5. BRL Memorandum Report No. 767, "Air Blast Measurements Around Moving Explosive Charges," J. D. Patterson and J. Wenig, March 1954.

6. BRL Memorandum Report No. 900, "Air Blast Measurements Around Moving Explosive Charges, Part II," B. F. Armendt, Jr., May 1955.

7. BRL Memorandum Report No. 977, "Qualitative Tests of Dynamic Strength of Various Plastic-Bonded and Fiber-Reinforced Explosives," B. F. Armendt, Jr., February 1956.

[redacted]

ADDENDUM

In the section on "Time of Arrival Data," page 14, the statement was made that the shock wave produced by the detonation of a moving spherical charge remains spherical, but the center of the sphere moves in the direction of motion of the charge prior to detonation. This statement was supported by experimental data obtained with twenty-four time-of-arrival gages. Assuming that the statement is correct, a simple mathematical analysis was made (see the section on "Theory" page 15.) Such a simple construction would not be possible if the shock wave produced by the moving charge were distorted (i.e., not spherical).

Since the original paper was presented at the Seventh AXP Tripartite Conference, additional information has been obtained by D. J. Hinz, of the Ballistic Research Laboratories, using a photographic method. A spherical charge of fiberglas-reinforced Pentolite was projected at approximately 1800 feet per second and detonated in flight as described under "Experimental Procedure," page 8 . The detonating charge was backlighted by means of an exploding wire placed at the focus of a 10-foot parabolic reflector. A camera facing in a direction normal to the line of flight and having a one-microsecond electronic shutter was synchronized with the exploding wire, and photographed the expanding shock wave. A sample photograph is shown in Figure 7, in which the shock wave has reached a diameter of approximately 58 inches. Close examination of the shock contour indicates that the shape is either spherical, or very close to it. This information substantiates the statement made in the original paper that the shock wave remains spherical.

The use of the above data, prior to publication by Mr. Hinz, is gratefully acknowledged.

[redacted]

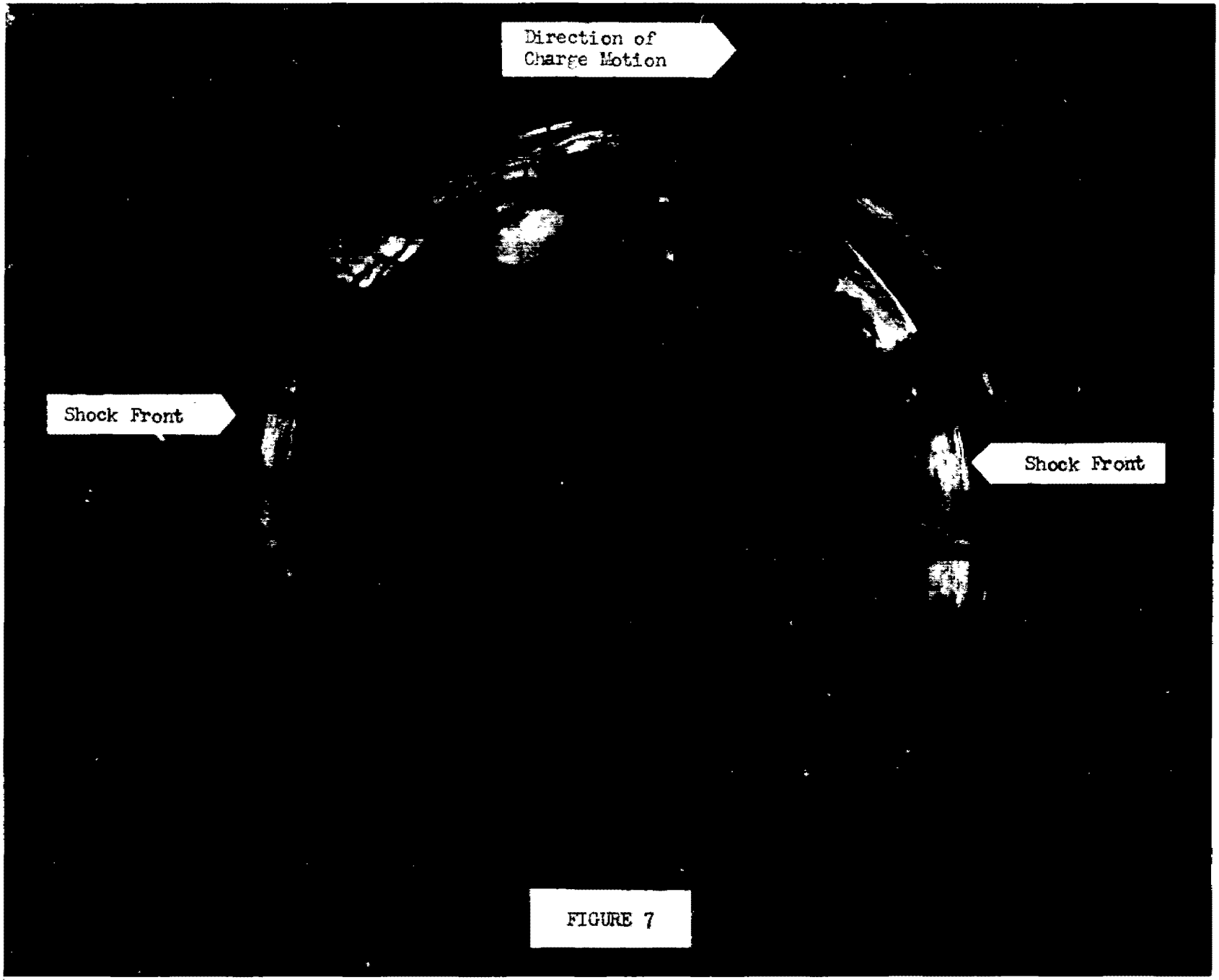

FIGURE 7

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